Accelerator Preparations for $\mu 2e$ Operation

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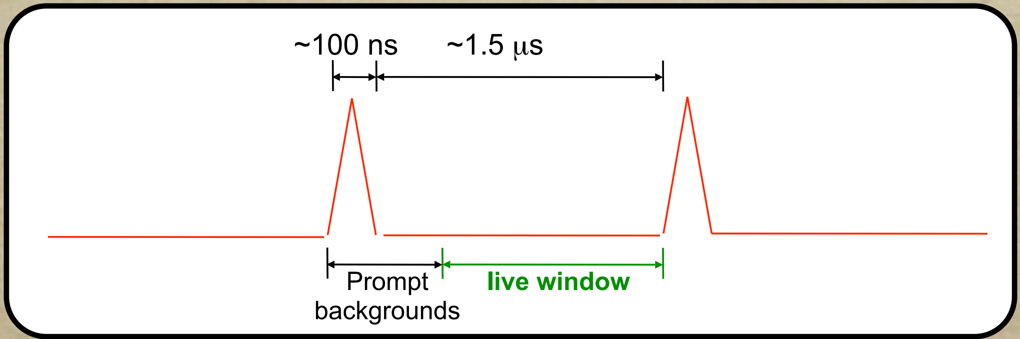
Experiment Requirements

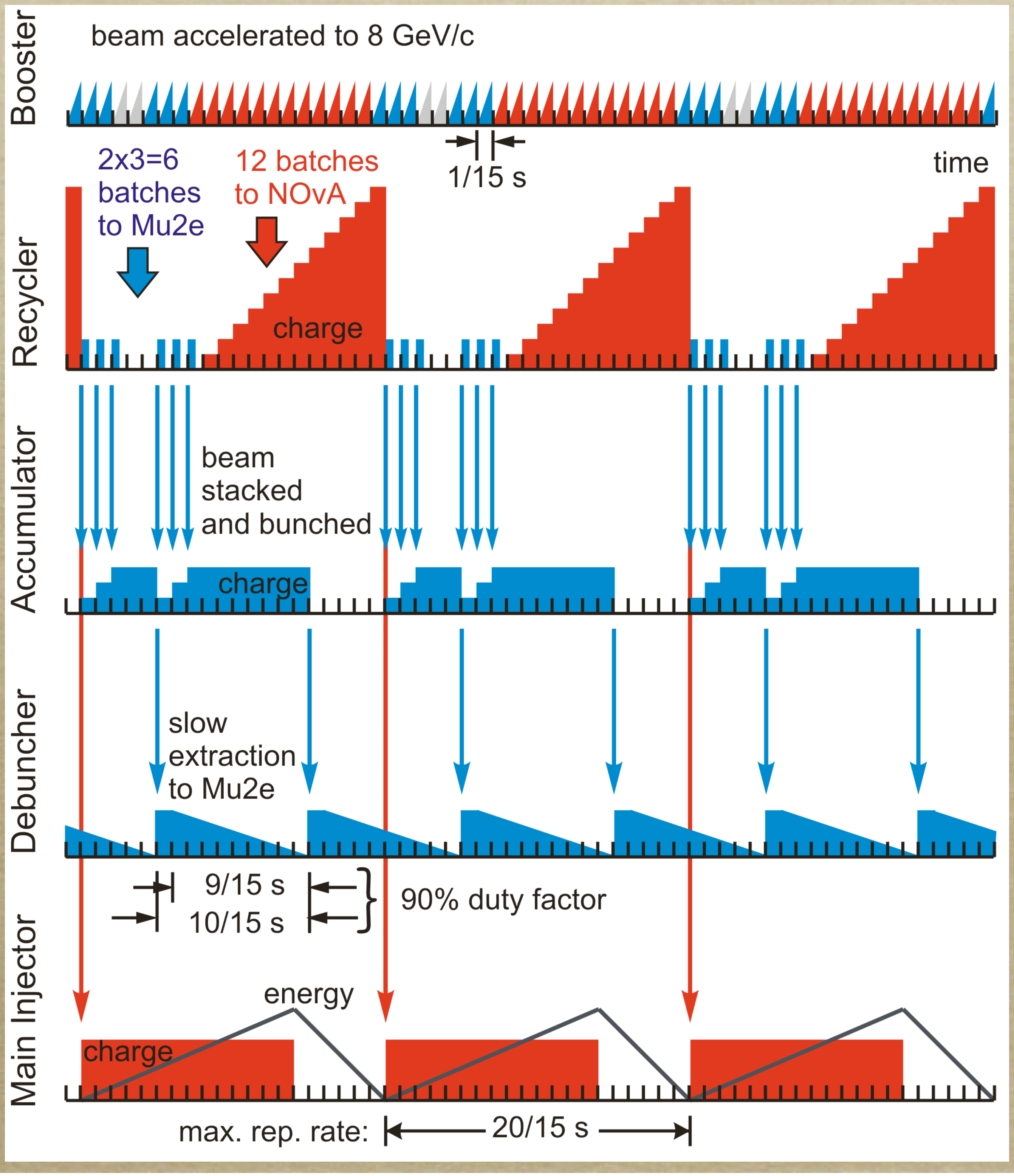
- *Requirments from accelerator facility:*
  - *$4x10^{20}$ protons on target, over ~2 years*
  - *~100 nsec time bursts,*
  - *~1.5 μsec spacing*
  - *10^{-9} extinction factor during data taking*



- *Assumes 15 Hz Booster is in operation*
- *Will not affect NOvA proton economics*

Meeting the Requirements

- *During "unused" Booster cycles, accumulate charge in Accumulator, x-fer and form single bunch in Debuncher; slow spill*
- *In principle, w/ $4x10^{12}$ (4 Tp) per Booster batch, Mu2e receives 18 Tp/sec on target, $1.8x10^{20}$ in 10^7 sec.*



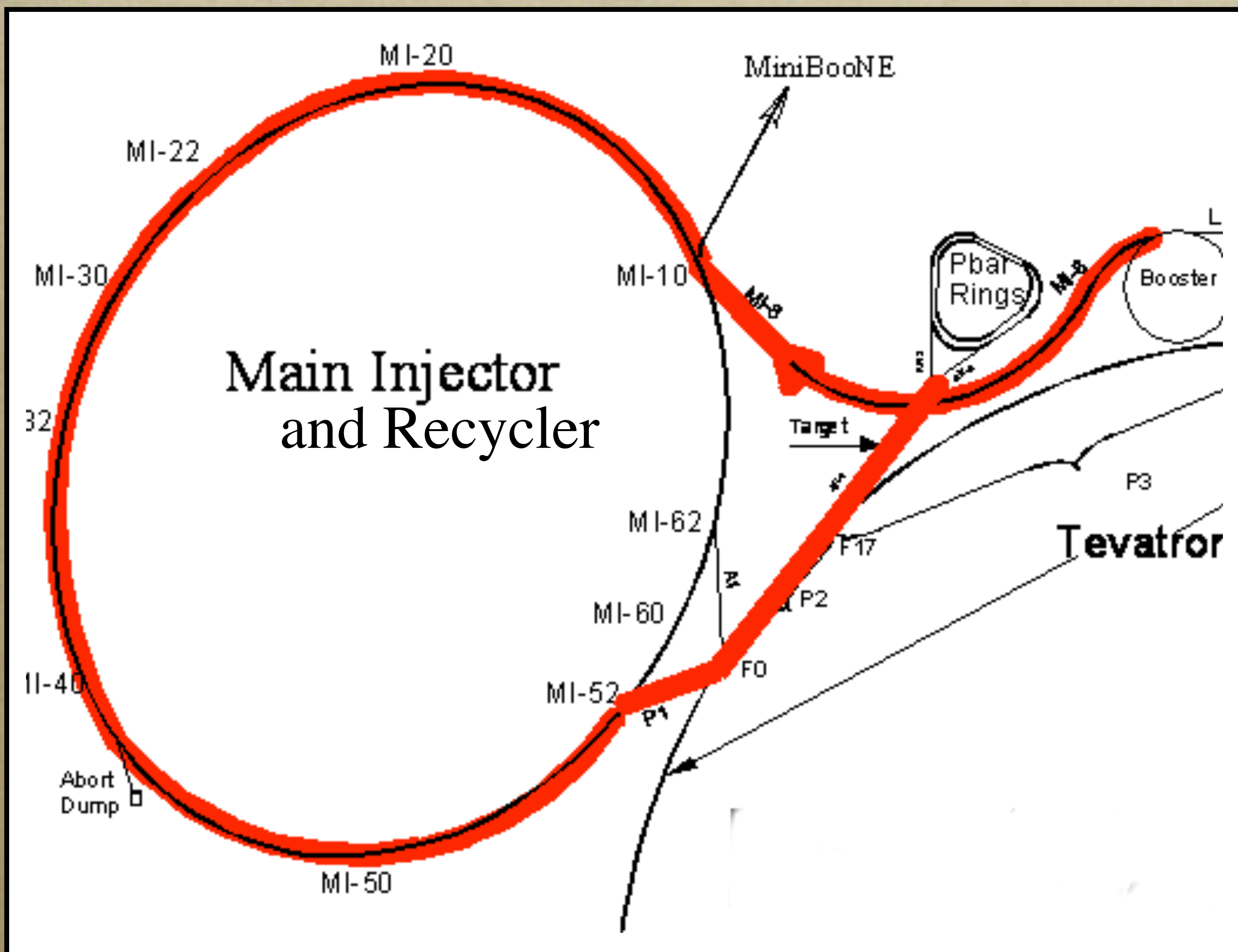
Meeting the Requirements

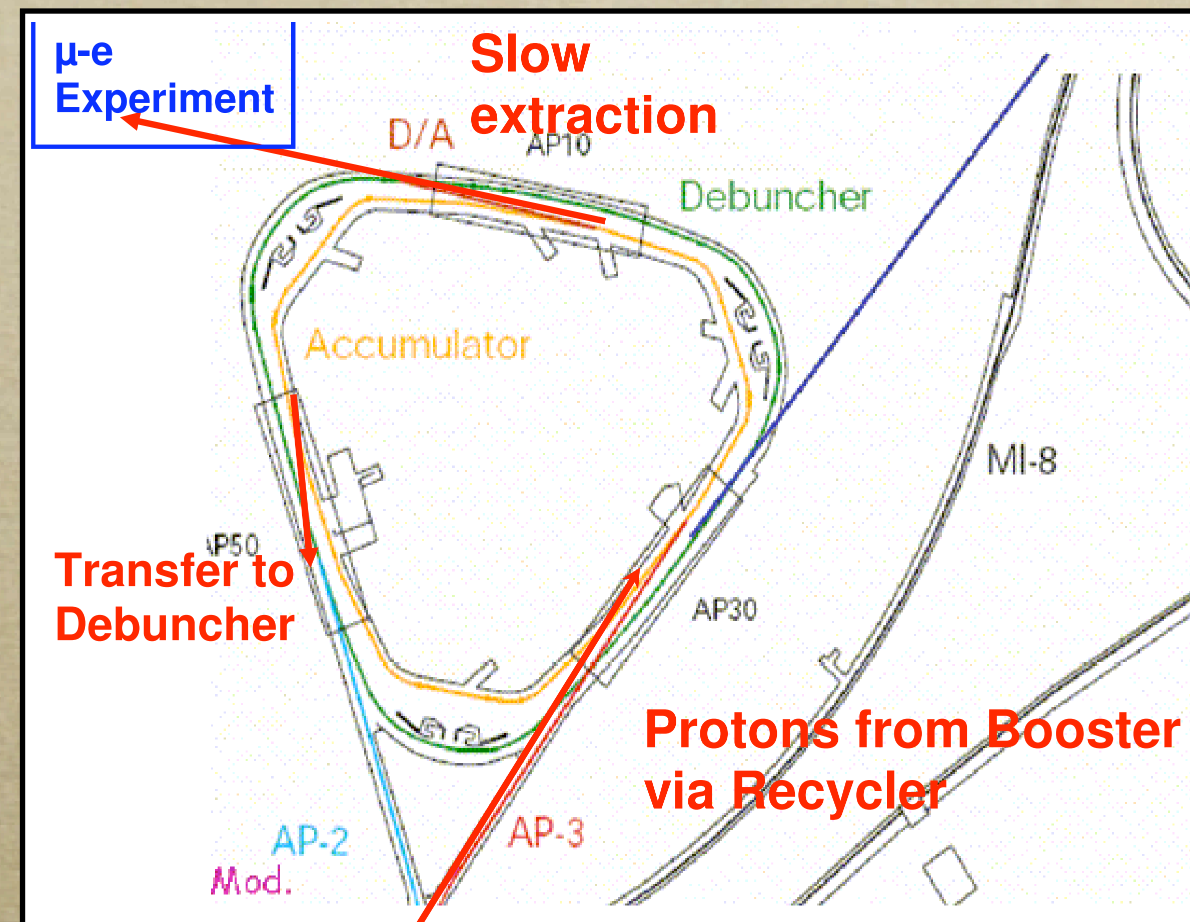
- *From the Debuncher, extract protons using slow resonant extraction technique.*
  - *make single bunch, with rms 40 nsec 'length'*
  - *particles emerge from ring in 40 nsec (rms) bursts, one burst every 1.7 μsec (revolution period of the Debuncher ring), ~3.4x10^7 per burst*
- *Deliver required 'extinction' using a special extinction channel in beam transport line*

Coming Up...

- *Beam Delivery*
- *Beam Preparation*
- *Slow Extraction*
- *Extraction Line and Extinction Channel*
- *Beam Intensity Issues*
- *R&D*

Beam Transport from Booster

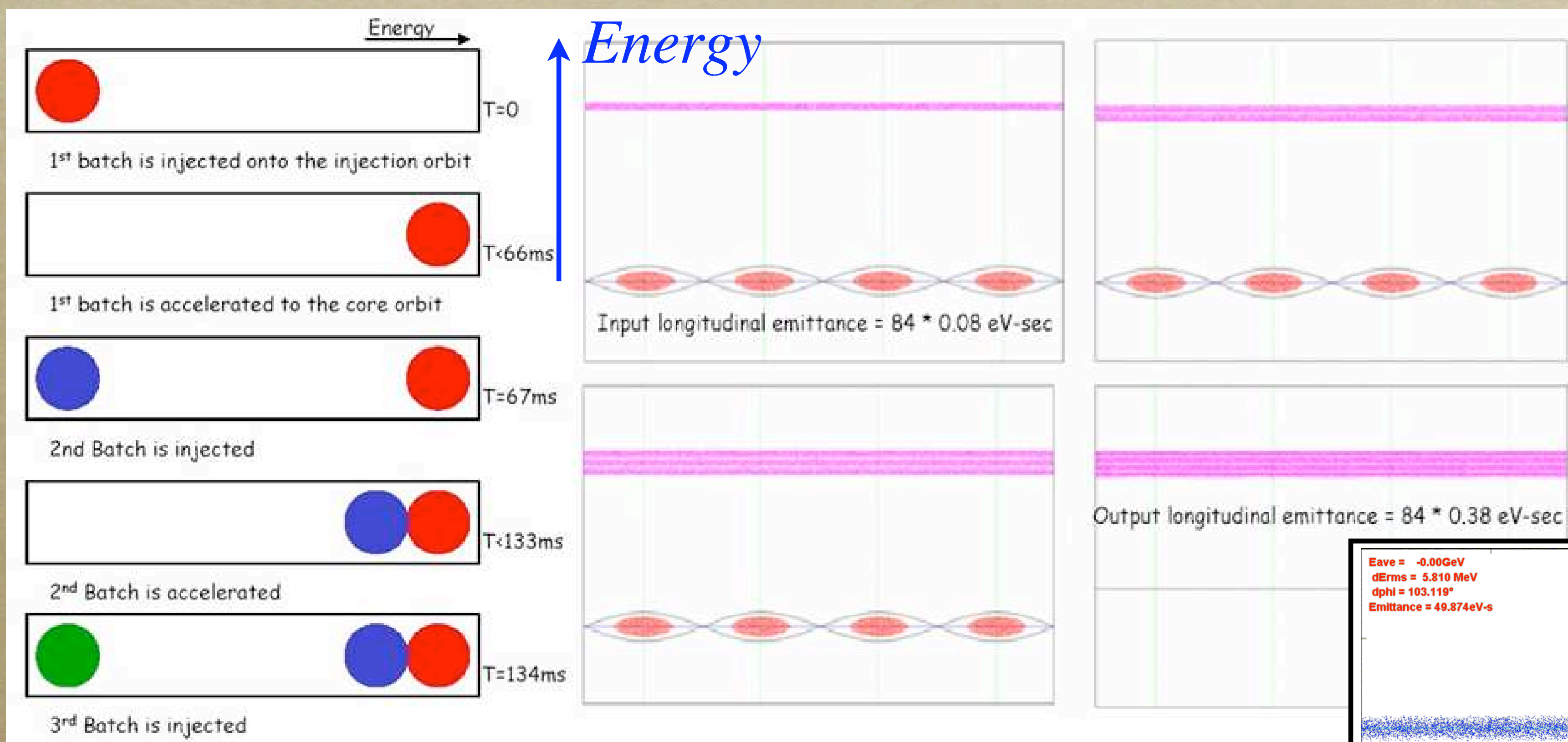


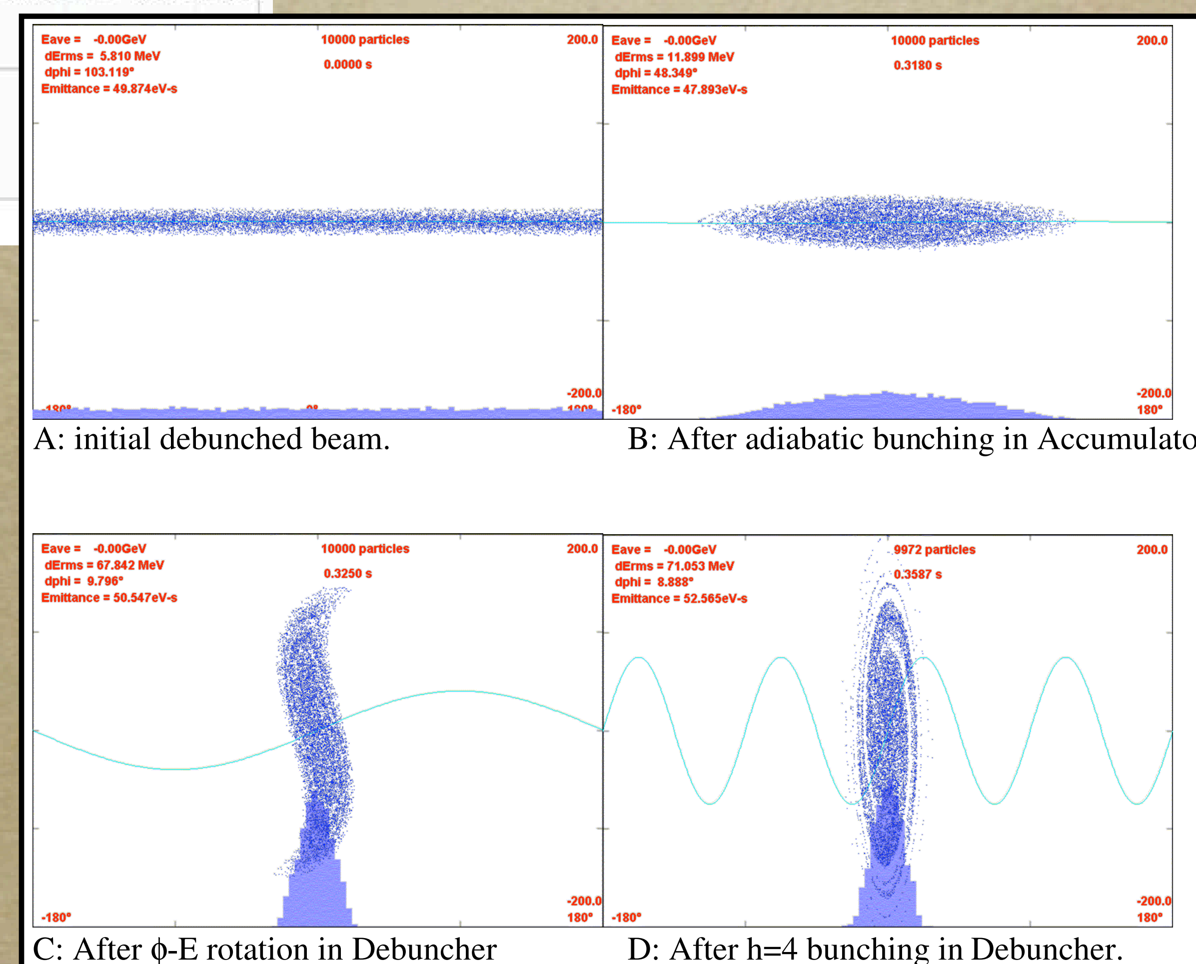


- *Requires:*
  - *inj/extr to/from RR ring; move D/A transfer AP10 -> AP50*

("into" is part of NOvA)

Beam Preparation





A: initial debunched beam.

B: After adiabatic bunching in Accumulator.

C: After ϕ-E rotation in Debuncher

D: After h=4 bunching in Debuncher.

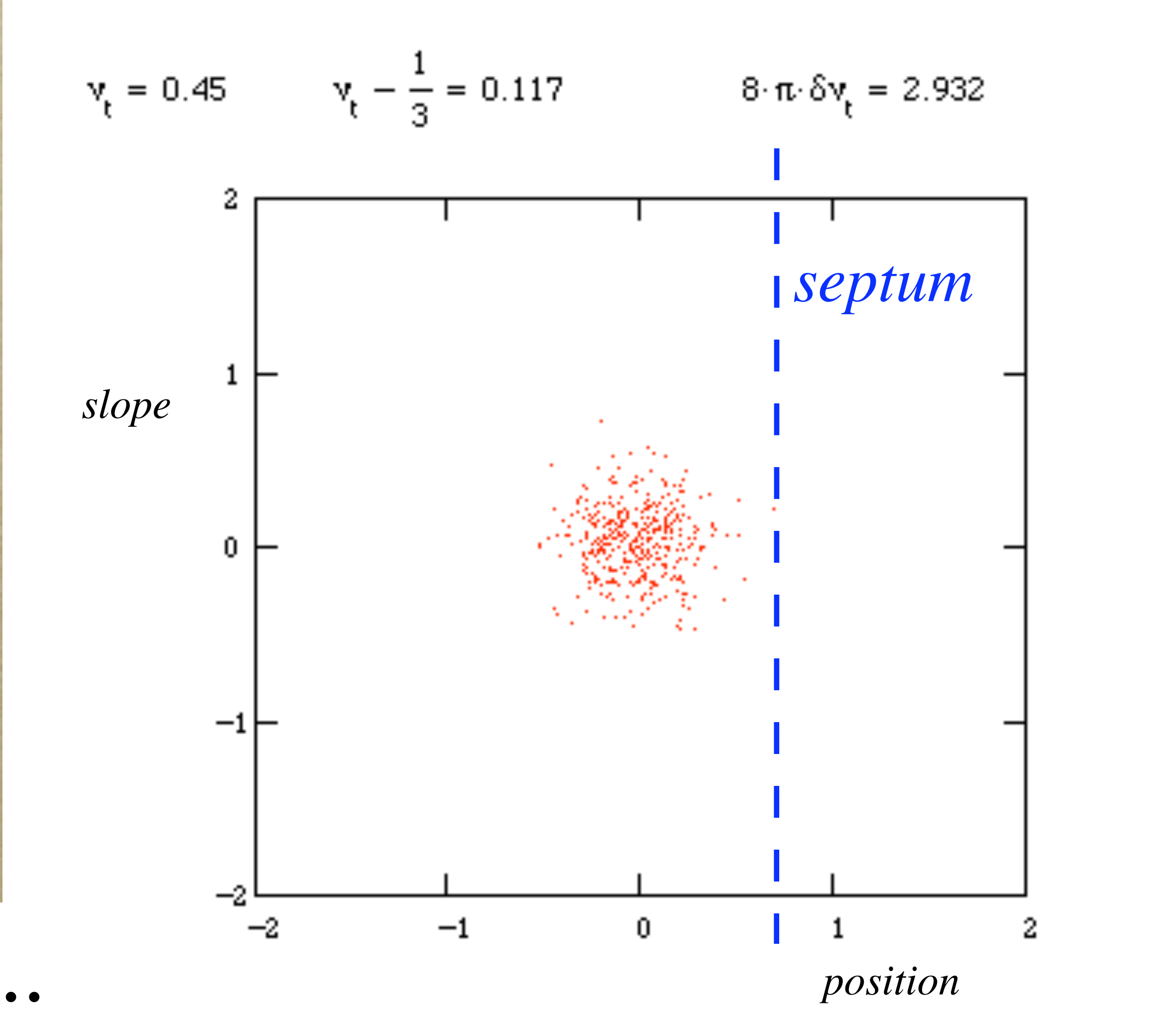
- *momentum stack in Accumulator*
- *form single bunch; x-fer to Debuncher*
- *phase rotate, re-capture*
- *40 nsec bunch, $\Delta p/p \sim 0.8\%$ (rms)*

RF Requirements

- Accumulator:
  - 53 MHz (h=84), 80 kV (~30-50 kV presently avail.)
  - 625 kHz (h=1), 4 kV (~2 kV presently available)
- Debuncher:
  - 588 kHz (h=1), 40 kV (~0.5 kV at present)
  - 2.35 MHz (h=4), 250 kV (~0.8-2 kV at present)
- Techniques are sound, technology known; cost estimate needs to be performed

Resonant Extraction

- *Once beam is in the Debuncher, "slow" spill over next 9 Booster cycles (600 msec)*
- *Resonant Extraction process*
  - *adjust betatron tune to be near rational value*
  - *use feedback to control rate of particle extraction*



generic example…

Resonant Extraction

- *half- vs. third-integer extraction*
  - *traditionally, Fermilab has used half-integer resonances for extraction; at final stage, can put ALL beam on resonance and extract every particle*
  - *with third-integer, always some beam left over, which must be aborted prior to next injection*
- *First-pass simulation was performed using 3rd-integer, with Debuncher ring parameters*

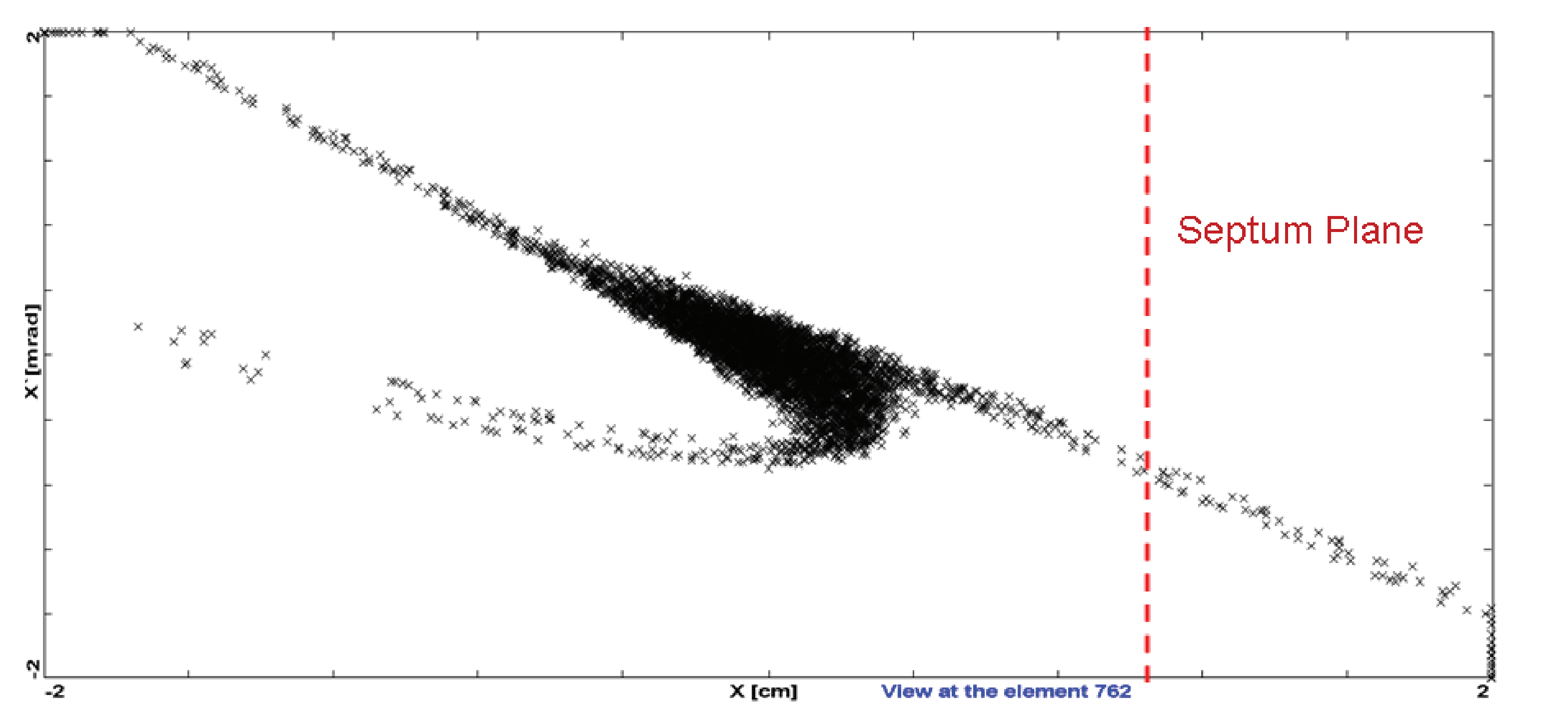
Slow Spill from Debuncher (*prelim.*)

Table 1.1: The approximate parameters of the third order resonant extraction, with the septum located between the Q101 and Q602 quadrupoles.

Kinetic Energy (GeV)	8
Working tune (ν_x/ν_y)	9.769/9.783
Resonance (ν_x)	29/3
Normalized acceptance (x/y π-mm-mr)	285/240
Normalized beam emittance (π-mm-mr)	20 π
β_x at electrostatic septum (m)	15 π
β_x at Lambertson (m)	22 π
β_x at harmonic sextupoles (m)	14
Septum Position (mm/σ)	11/4.8
Septum gap/step size (mm)	10
Sextupole Drive Strength (T-m/m2)	473
Initial Tuneshift ($\delta\nu$)	.048
Septum field (MV/m)	8
Septum length (m)	3

- *Debuncher lattice and realistic magnetic elements used in simulation*
  - *(no space charge)*

- *Phase Space Results*
  - *inefficiency: wire thickness over "step size":*
    - *~ 0.080 mm/10 mm ~ 1%*



Extraction Issues

- *For MR, Tevatron, MI operation, momentum spread was always relatively small ($<10^{-4}$)*
- *Here, as seen previously, expect:*
  - *200 MeV/8.9 GeV ~ 2% (full width)*
  - *needs careful analysis; space charge also an issue*
  - *Note: AGS uses(d) 3rd-integer w/ large $\Delta p/p$, but beam was "debunched"*
    - *will require fine control of chromaticity, or perhaps some new scheme*

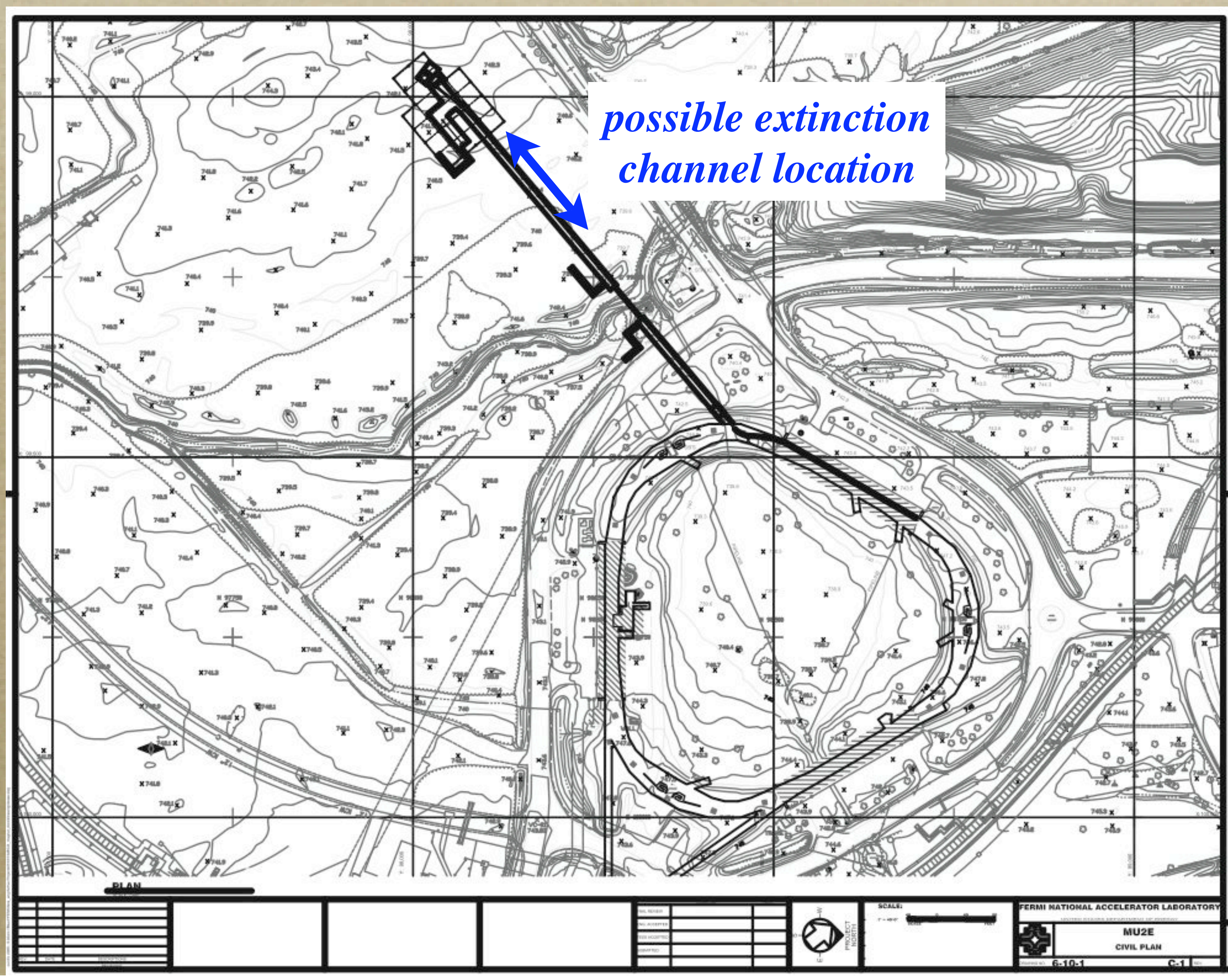
Extraction Issues

- *Will look further at Debuncher extraction with large momentum spread and space charge*
  - *perhaps examine other/new schemes*
- *Note: necessary equipment for the baseline design is understood -*
  - *electrostatic, magnetic septa*
  - *correctors, feedback circuitry*

Extraction Line and Extinction

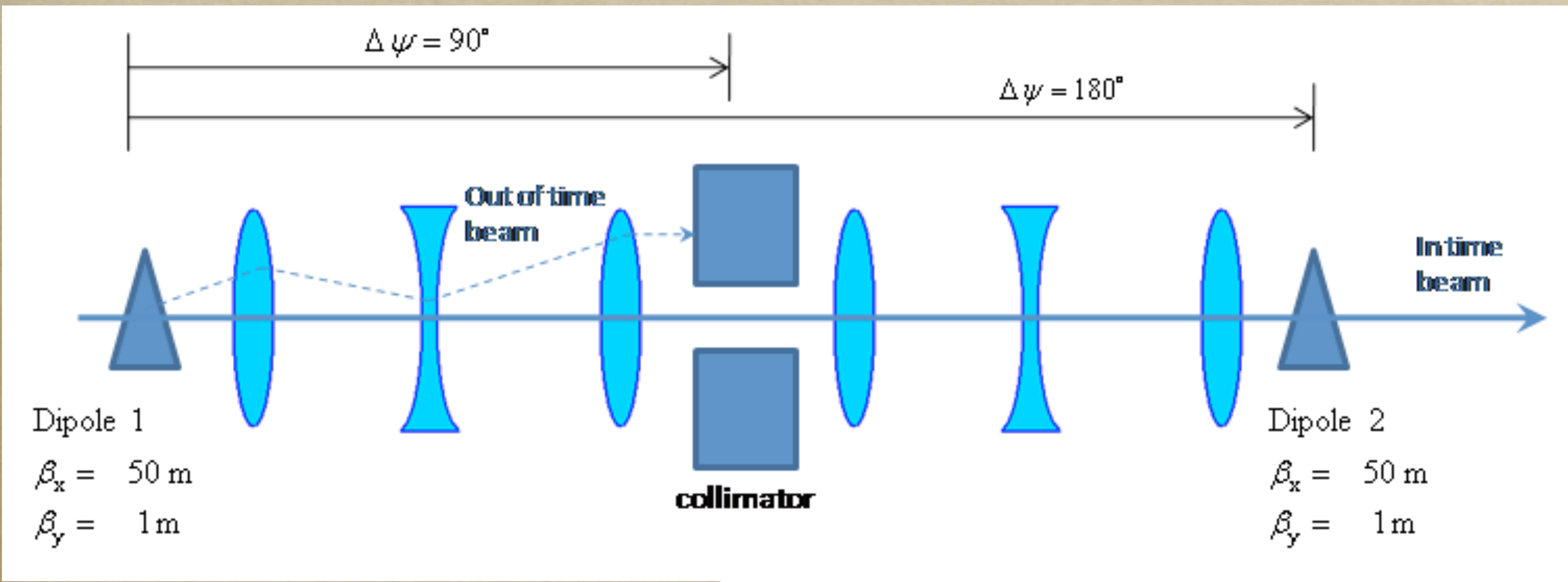
- *Baseline layout of beam line*
    - *constraints:*
        - *extract from AP10 region*
        - *exit tunnel at an "appropriate" angle*
        - *pass under creek (to avoid wetland issues)*
        - *include/match to extinction channel*
        - *final focus onto target*

design work is just beginning…



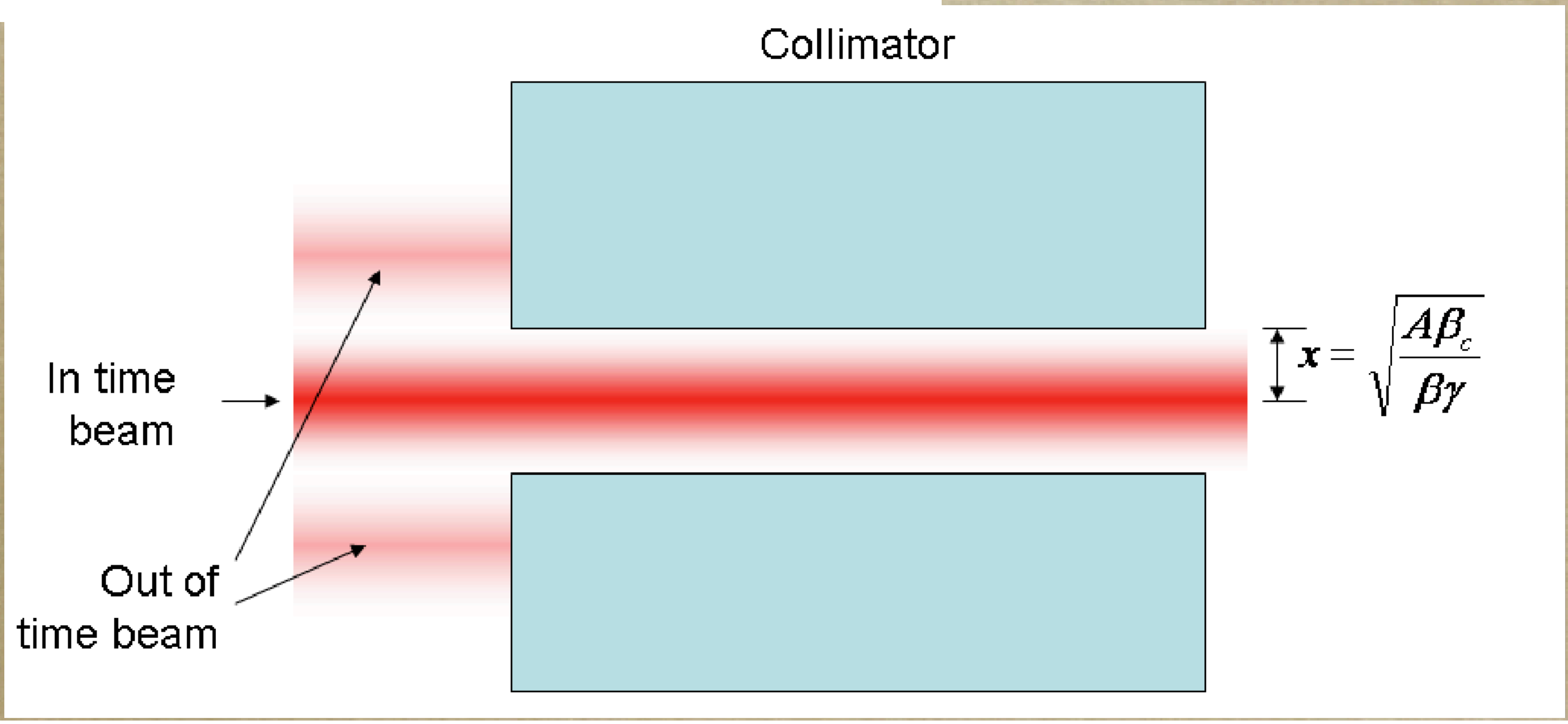
Extinction Channel Concept

(proof of principle)

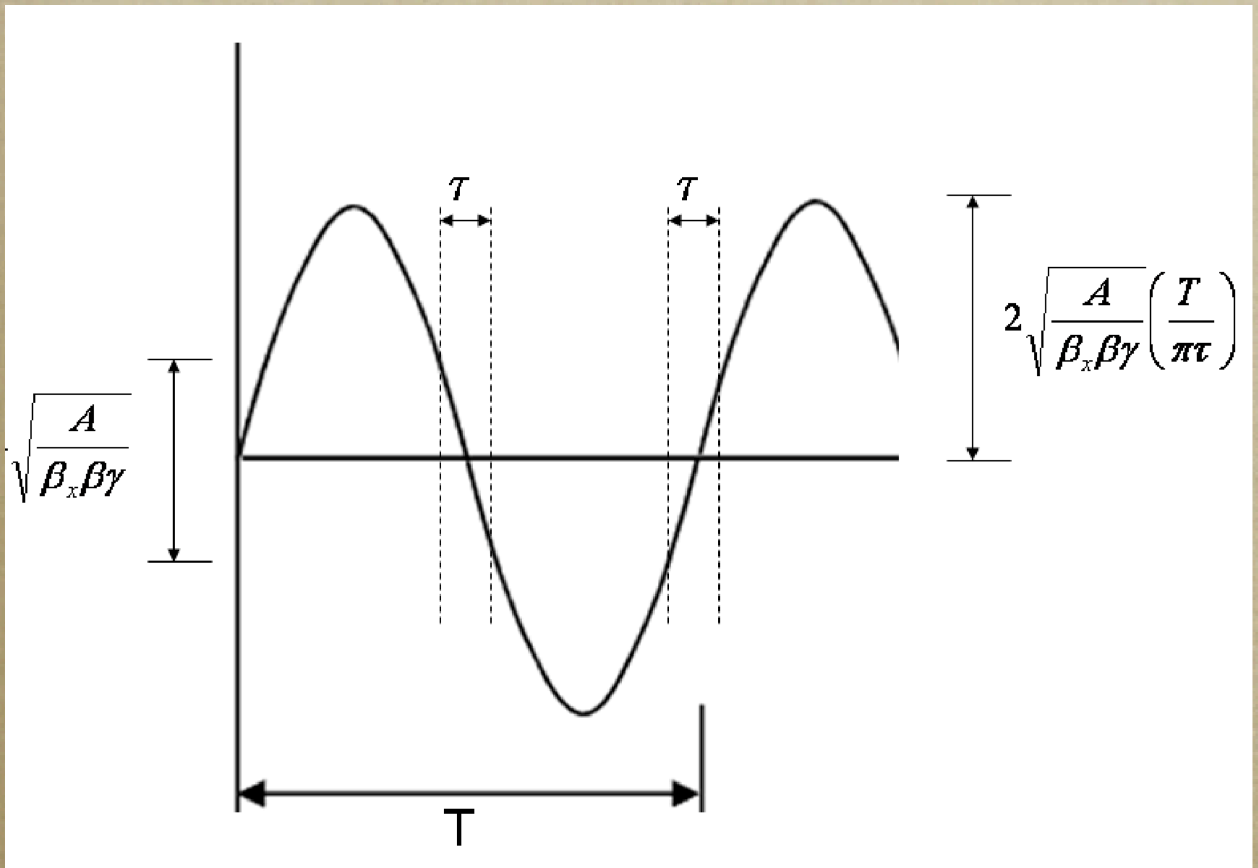


- *design channel as part of transport line between Debuncher and experiment*

- *"AC dipoles" kick out-of-synch particles into collimators*



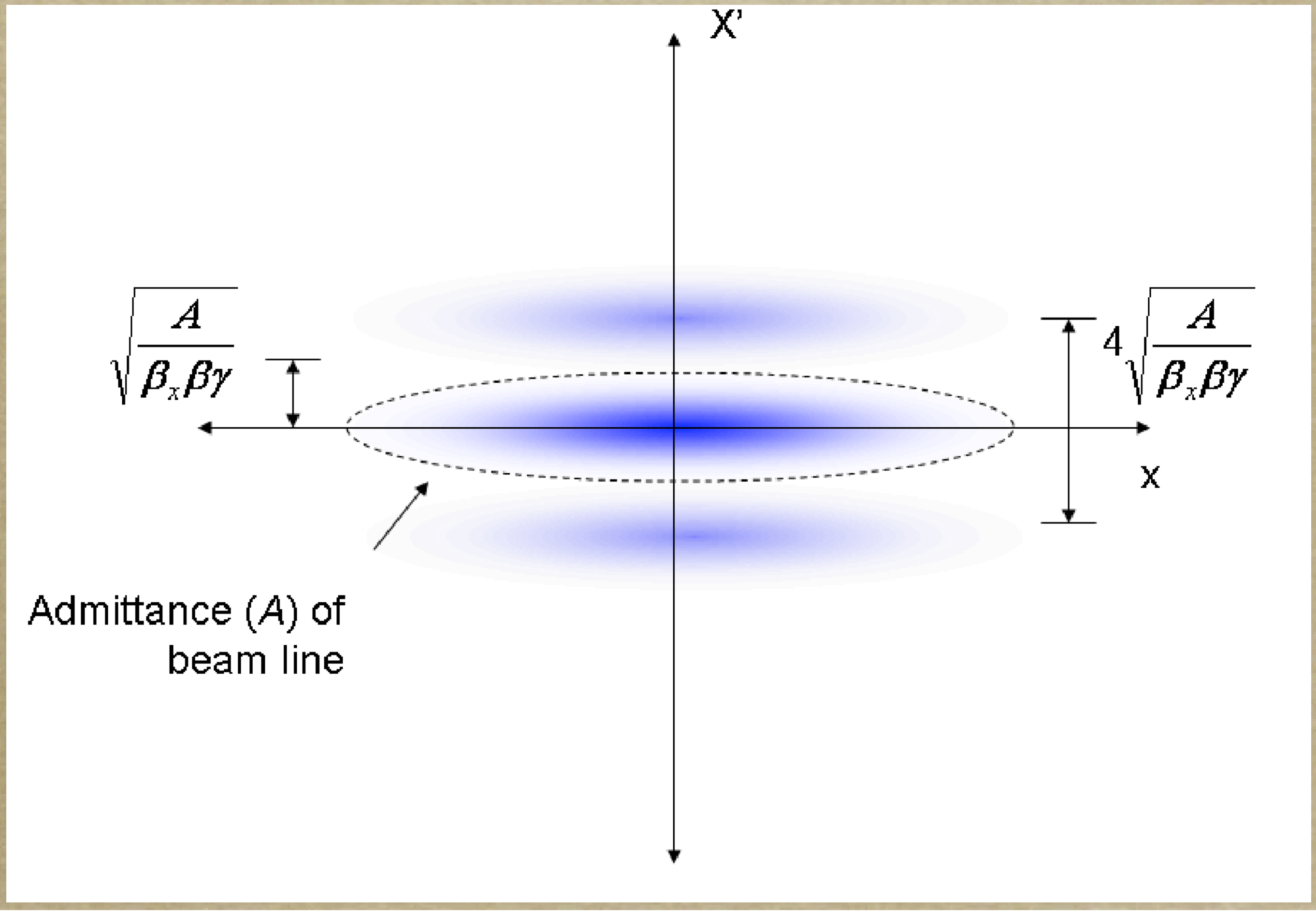
AC Dipole Requirements



- *Optical design and extinction requirement will determine amplitude of kick*

- *Dipole frequency:*

  $^1/_2$ Debuncher revolution frequency ~ 300 kHz



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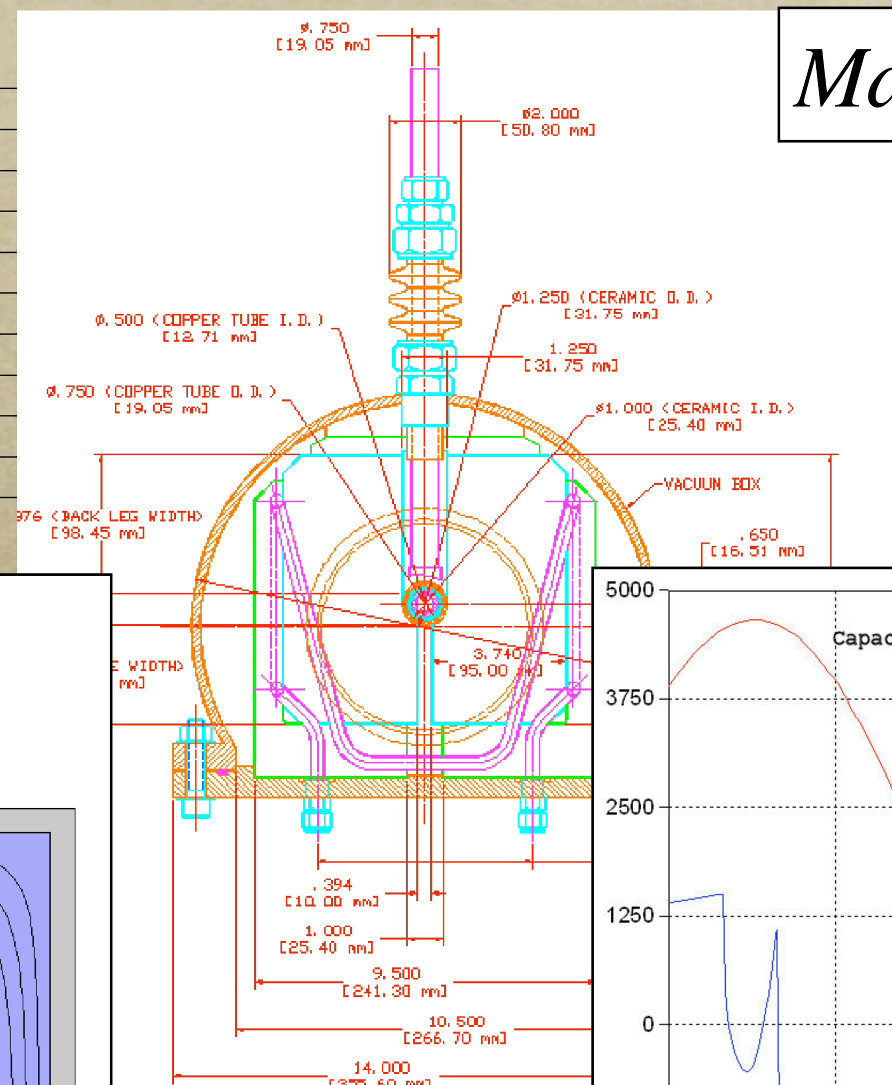
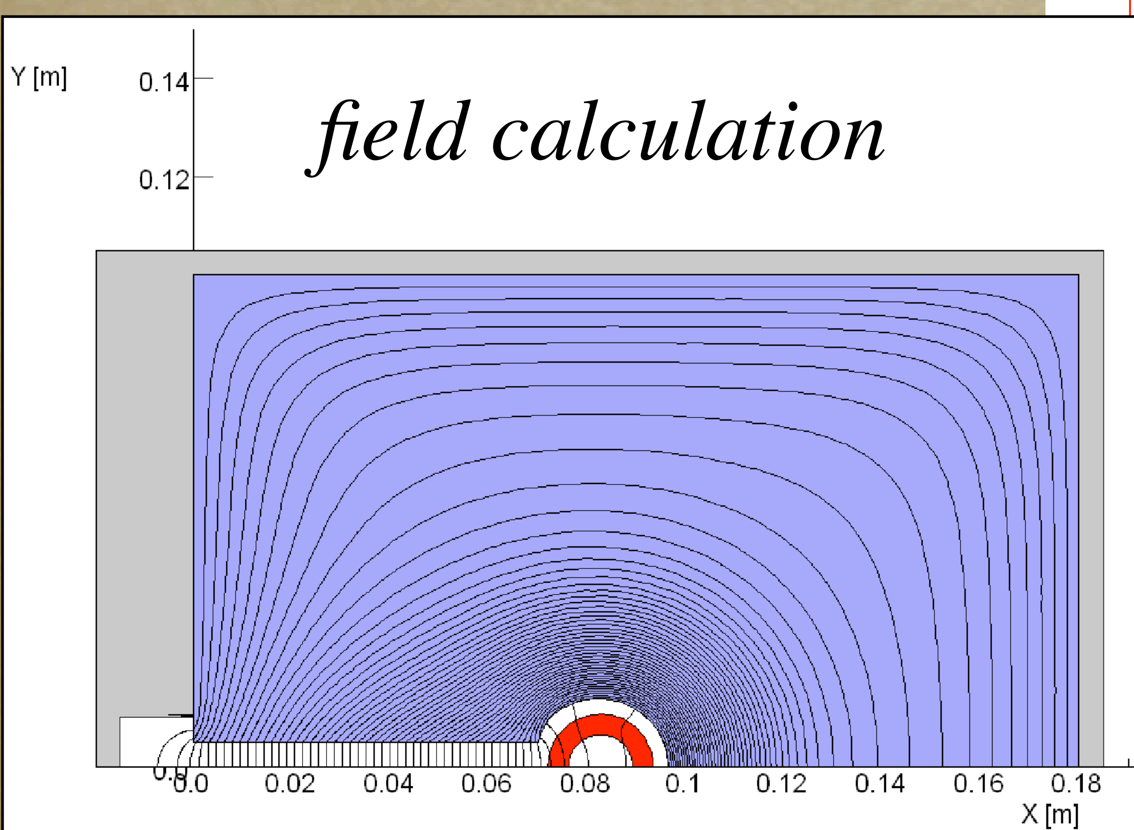
AC Dipole System R&D

Table I. AC Dipole specification.

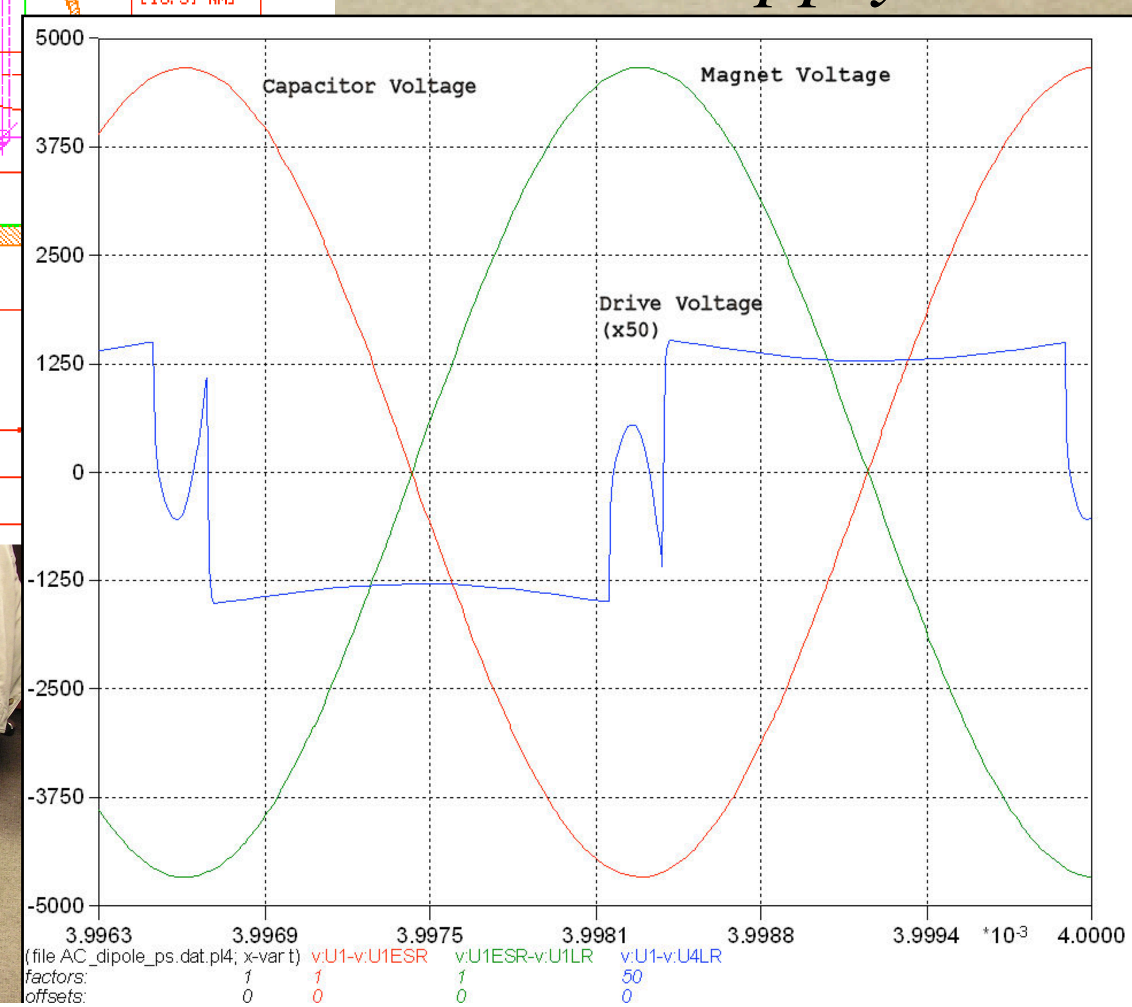
Parameter	Unit	Value
Integrated strength	T-m	0.12
Magnet gap	mm	10
Effective length	m	2.0
Good field area width	mm	50
Center field	T	0.06
Current form		Sine wave
Current frequency	kHz	300
Operational regime		Continuous
Radiation level		low

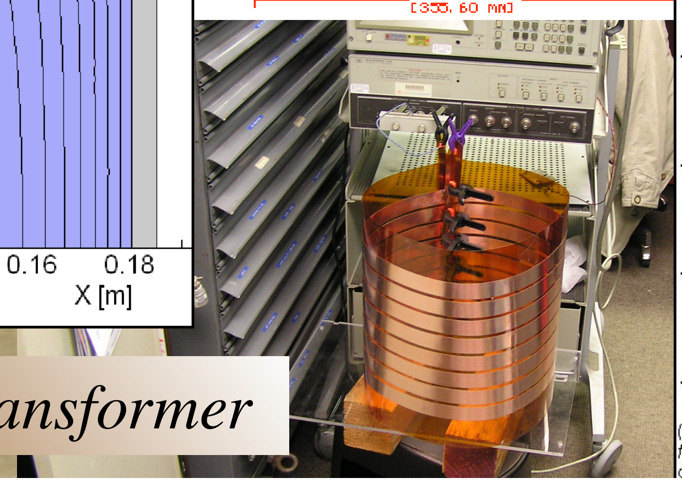
Magnet Design





Power Supply Calc





prototype transformer

Beam Flux and Radiation Safety

- *New particle rates for the "pbar" rings:*
  - *presently, Debuncher/Accumulator receive approximately 25×10^{10} particles per hour; for μ2e, expecting ~2×10^{13} per second: factor of 300,000*
  - *1% loss (scaling) ➞ ~290 W of beam loss power*
    - *Booster: ~500 W total, ~1 W/m (300 W, 0.6 W/m in uncontrolled regions)*
- *Will require new mitigation for "pbar" rings*
  - *passive system not enough; need ~ Booster system*
  - *const. energy rings help -- can monitor devices, inhibit beam*

Critical Issues

- *Intensity Limitations:*
    - *Better estimates should be performed on foreseen intensity limitations of Accum/Deb rings. At design intensity, space charge can be appreciable. Assess aperture and impedance of the reconfiguration.*
- *RF requirements:*
    - *Further optimization of the momentum stacking and bunch formation processes should be considered and parameters finalized.*

Critical Issues

- *Resonant Extraction:*
  - *Develop the plan for resonant extraction and its modeling, including the effects of beam momentum spread, space charge, and realistic apertures. Alternate schemes, such as "pinging" and "microbunching" may be examined if necessary. Extraction inefficiency needs to be better estimated. The requirements and expectations for the slow spill feedback circuit need to be developed.*

Critical Issues

- *Extraction Line:*
  - *A full design is required, including extinction channel; fully determine physical constraints between the ring and experimental hall.*
- *Extinction Channel:*
  - *Take from conceptual layout to an engineering design, along with appropriate specifications for the required instrumentation for measuring and monitoring the level of achieved extinction.*

Critical Issues

- *Radiation Safety:*
  - *Perform careful analysis of necessary safeguards for running high intensity beams in the antiproton enclosures. Passive, active safety measures will need to be designed and costed.*
- *Instrumentation:*
  - *Perform analysis of the present instrumentation and possible modifications or upgrades necessary to monitor bunched beam.*

How to Address...

- *So far, following scientific help from FNAL are involved:*
    - *Overall: Syphers, Prebys, Popovic, Ankenbrandt (ret.)*
    - *RF gymnastics: Neuffer* - *Spill: J. Johnstone*
    - *Beam Line: C. Johnstone* - *Deb/Accum rings: Werkema*
- *Committee's strong support can help acquire further (real) eng/sci support*

First-Pass Cost Estimate

	M&S (K$, FY08)	Sr Eng (FTE)	Eng (FTE)	Sr Tech (FTE)	Tech (FTE)	Designer (FTE)	Total Labor (K$, FY08)	(no contingency) (K$, FY08)	Contg. (%)	Contg. (%)	Sub Total (K$, FY08)	Notes/BOE
Common Requirements												
RR Injection Line, from MI-8	**2186**							**2186**			**2514**	*part of NOvA / ANU*
beam line	537	0	0	0	0	0		537	15%	35%	618	*(Popovic)*
injection kicker	1649	0	0	0	0	0		1649	15%	35%	1896	*(Mu2e-268)*
RR Extraction Line, to P-1	**732**						**1313**	**2045**			**2760**	
beam line	732	4.64	0	0	0	0	1313	2045	35%	35%	2760	*(Popovic)*
15 Hz operation	**1517**						**369**	**1886**			**2451**	
Booster RF upgrade	1517	0.25	0	0	2	0	369	1886	30%	30%	2451	*8/21/08 Memo, Reid*
								6116			**7725**	**TOTAL**
mu2e												
RR Extraction	**97**	0.00	0.00	0.00	0.00	0.00	**71**	**168**			**150**	*(choose lesser of two)*
kicker (if modified from g-2)	22	0.25	0.00	0.00	0.00	0.00	71	93	100%	100%	0	*(10% of g-2 kicker cost), or*
or, switched magnet system	75	0.00	0.00	0.00	0.00	0.00	0	75	100%	100%	150	*basic magnet + P.S.*
AR RF systems	**700**	0.00	0.00	0.00	0.00	0.00	**550**	**1250**			**2500**	
53 MHz (h=84), 50 kV	300	0.50	0.50	1.00	1.00	0.00	550	850	100%	100%	1700	*guess; upgrade to existing system*
625 kHz (h=1), 4kV	400	0.00	0.00	0.00	0.00	0.00	0	400	100%	100%	800	*guess; check w/ Wildman*
DR RF systems	**1200**	0.00	0.00	0.00	0.00	0.00	**982**	**2182**			**4364**	
588 kHz (h=1), 40 kV	400	0.50	0.50	1.00	1.00	0.00	550	950	100%	100%	1900	*guess; check w/ Wildman*
2.35 MHz (h=4), 250 kV	800	0.25	0.25	1.00	1.00	0.00	432	1232	100%	100%	2465	*guess; based on g-2 numbers*
DR slow spill system	**500**	0.00	0.00	0.00	0.00	0.00	**213**	**713**			**1425**	
electrostatic septum	250	0.00	0.00	0.50	0.00	0.00	95	345	100%	100%	689	*guess*
magnetic septum	150	0.00	0.00	0.00	0.00	0.00	0	150	100%	100%	300	*guess*
resonance feedback system	100	0.25	0.00	0.25	0.00	0.00	118	218	100%	100%	436	*guess; correctors + electronics*
Beam Line to Target (not civil construction)	**1030**	1.00	1.00	2.00	2.00	0.00	**1100**	**2130**	100%	100%	**4259**	*scaled from NOvA*
Extinction Channel	**470**	0.00	0.00	0.00	0.00	0.00	**877**	**1347**			**2695**	
AC dipole	250	0.50	0.50	1.00	1.00	0.00	550	800	100%	100%	1600	*guess; TD memo*
AC dipole power supply	120	0.33	0.17	0.33	0.17	0.00	210	330	100%	100%	659	*Wolff Memo*
collimator system	100	0.25	0.00	0.25	0.00	0.00	118	218	100%	100%	436	*guess; ~ Boo/MI collimator*
Radiation Safety	**500**	0.00	0.00	0.00	0.00	0.00	**0**	**500**			**1000**	
AR, DR rings	400	0.00	0.00	0.00	0.00	0.00	0	400	100%	100%	800	*guess*
Extinction Channel Region	100	0.00	0.00	0.00	0.00	0.00	0	100	100%	100%	200	*(<< above line)*
Instrumentation and Controls	**250**	0.00	0.00	0.00	0.00	0.00	**0**	**250**			**500**	
AR, DR, AP1-3 BPM upgrade	250	0.00	0.00	0.00	0.00	0.00	0	250	100%	100%	500	*guess*
								8539			**16893**	**TOTAL**

Summary

- *First-pass look at all aspects performed, basic concept looks sound*
- *Baseline decoupled from Project X*
- *Accelerator issues identified, "plan" + initial cost estimate are under further development*
- *Accelerator working meetings have begun*

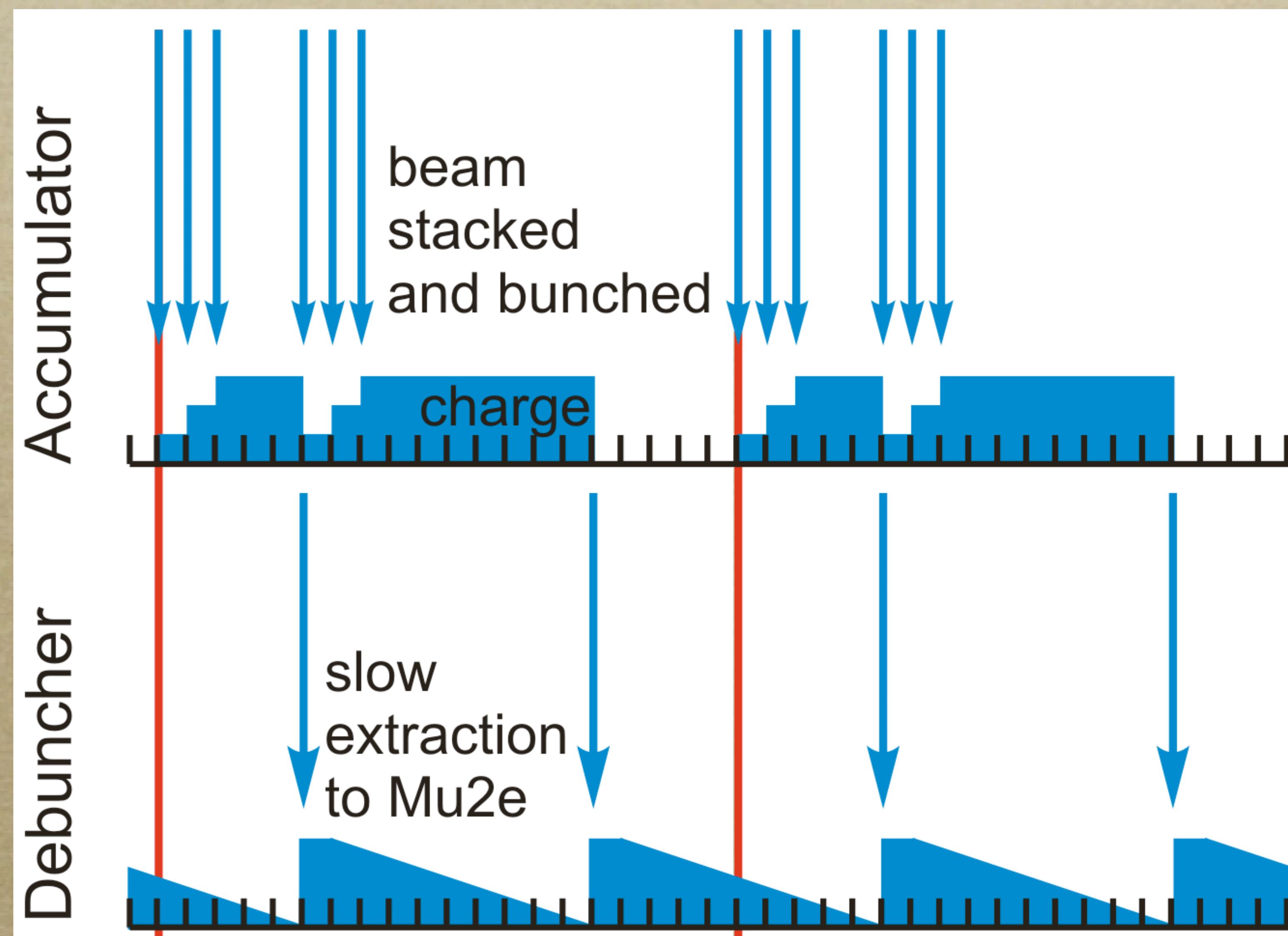
References

- *Fermilab Proton Plan, see: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml.*
- *D. McGinnis, "Beam Emittances and RF structure at Injection into the Main Injector for the Multi-Stage Proton Accumulator," Beams-doc-2138 (2 Feb 2006).*
- *J. Reid, R. Ducar, "Booster RF Repetition Rate Limit," Beams-doc-2883 (7 May 2007).*
- *Mu2e Collaboration, "Expression of Interest to Fermilab," MU2E-doc-15 (1 Feb 2008).*
- *D. Neuffer, "More Rebunching Options for the mu2e Conversion Experiment," Beams-doc-2787 (21 May 2007).*
- *Mu2e Collaboration, "Proposal to Search for $\mu{-}N \rightarrow e{-}N$ with a Single Event Sensitivity Below 10^{-16} ," MU2E-doc-62 (15 Sep 2008).*
- *E. Prebys, "Optimizing AC Dipole Specifications for Beam Extinction," Beams-doc-2925 (7 Nov 2007).*
- *V.S. Kashikhin, D. Harding, V.V. Kashikhin, A. Makarov, D. Wolff, "Conceptual Design of AC Dipole Magnet for μ to $e-$ Experiment," MU2E-doc-263 (20 Aug 2008).*

Back-up Slides

When NOνA is "off"

- *If have all Booster Cycles available for use in Mu2e:*
  - *Same fill scenario; assume can "spill" over 4 cycles rather than 9. Then,*
    - *4/5 = 80% duty cycle*
    - *36 Tp/sec (ave.)*
    - *45 Tp/sec (spill)*
    - *7.7×10^7 per "burst"*



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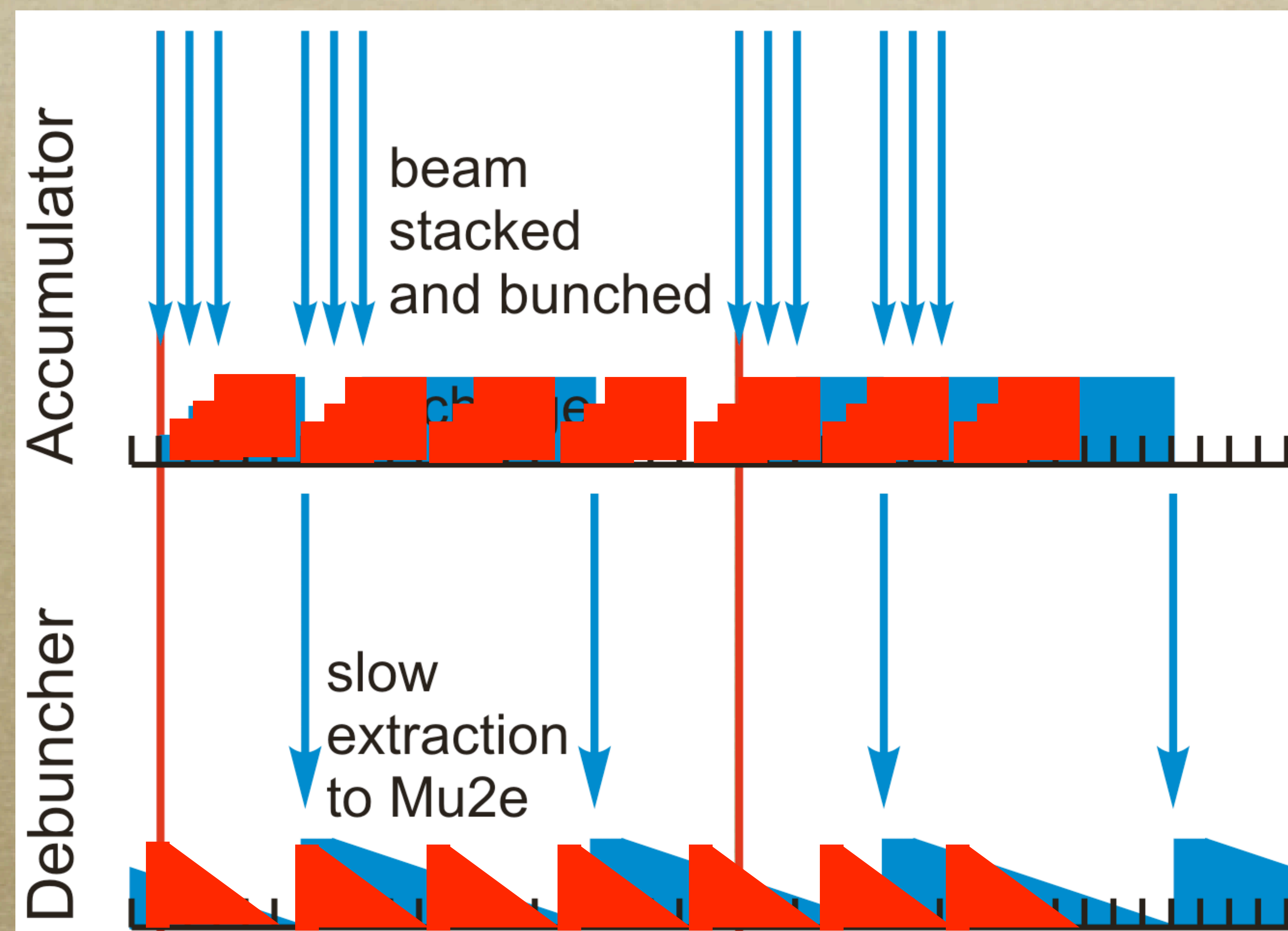

Space Charge Tune Shift

- *For N particles uniformly distributed about the ring,*

$$\Delta\nu_{s.c.} = \frac{3r_0N}{2\epsilon\gamma^2(v/c)} = \frac{3\ (1.5\times10^{-18})(1.2\times10^{13})}{2\ (20\pi\times10^{-6})(9.5^2)} \approx 0.005$$

- *Include "bunching factor":*

$$\mathcal{B} \approx \frac{1700\ \text{nsec}}{40\ \text{nsec}\cdot\sqrt{2\pi}} \approx 17$$

- *Thus, expect at design intensity:*

$$\Delta\nu_{s.c.} \approx 0.1$$

Debuncher Aperture

- *gap height: 2.375 in.* = ± 30 mm
- *good field width: 4 in.* = ± 50 mm

- Extraction:
  - in simulation above, step size = 10 mm; 20π emitt.
  - if double beam dimensions, can quadruple emittance, mitigating space charge somewhat